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A Coverage-Based Scheduling Algorithm for WSNs

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Abstract: Node scheduling in Wireless Sensor Networks (WSNs) plays a vital role in conserving energy and lengthening the lifetime of networks, which are considered as prime design challenges. In large-scaled WSNs, especially where sensor nodes are deployed randomly, 100% coverage is not possible all the times. Additionally, several types of applications of WSNs do not require 100% coverage. Following these facts, in this paper, we propose a coverage based node scheduling algorithm. The algorithm shows that by sacrificing a little amount of coverage, a huge amount of energy can be saved. This, in turns, helps to increase the lifetime of the network. We provide mathematical analysis, which verifies the correctness of the proposed algorithm. The proposed algorithm ensures balanced energy consumption over the sensor networks. Moreover, simulation results demonstrate that the proposed algorithm almost doubles the lifetime of a wireless sensor network by sacrificing only 5% to 8% of coverage.

Keywords: WSN, node scheduling, coverage, deployment density, coverage ratio.

1 Introduction

Node scheduling algorithms are extensively used in Wireless Sensor Networks (WSNs) to preserve energy consumption [1, 2, 3, 4, 5]. In these techniques, some sensor nodes are put in sleep mode, whereas the other sensor nodes are kept in active mode for sensing and communication tasks. When a sensor node is in sleep mode, it shuts down all functions, except for a low power timer to wake itself up at a certain time as defined by its node scheduling protocol [6]. Therefore, the sensor node consumes only a tiny fraction of the energy, compared to the energy consumed when the sensor node is in active mode all the time [7, 8, 9].

In WSNs, due to the limited resources and vulnerable nature of individual sensor nodes, sensors are deployed with high density (up to 20 nodes/m^3) [10]. As a result, the same area is covered by many sensor nodes. This causes heavy redundancy because multiple sensor nodes consume energy to sense the same area, and also to send/receive the identical data. In addition, higher node density incurs more contentions among neighbouring nodes [11]. As a result, additional time slots are required to implement time division multiple access (TDMA) techniques. The solution to avoid this redundancy is to turn off the redundant nodes, because turning off some nodes does not affect the overall system functions as long as there are enough working nodes to provide the services [12, 13]. Turned-off sensor nodes save a significant amount of energy, and this addresses one of the main constraints of WSNs, which is limited energy. Therefore, if sensor nodes are scheduled to perform alternately, more energy can be saved, and the system lifetime is prolonged correspondingly. In addition to redundancy, it is also worth mentioning that not all applications of WSNs require 100% coverage of the target field [14, 15, 16]. Some 80% to 90% or even a smaller amount of coverage of the target field is adequate. For example, applications, such as tracking humidity or temperature in an area, detecting forest fire etc. do not require 100% coverage by the deployed sensor nodes. It has been shown that sacrificing a little coverage substantially reduces the total energy consumption of the networks [15] and thus helps to lengthen the lifetime of the network.

Following the principles described above various coverage based node scheduling algorithms have been proposed by researchers [12, 13, 22, 23, 24, 25]. For example, in [22], Xu et al. propose a node scheduling algorithm where a subset of nodes is maintained in working mode to ensure the desired sensing coverage. Working nodes continue working until they run out of their energy or until they are destroyed. A sleeping node wakes up occasionally to probe its local neighbourhood, and starts working only if there is no working node within its probing range. Geometrical knowledge is used to derive the relationship between probing range and redundancy. In this algorithm, the authors assume that all nodes have the same sensing ranges to calculate the desired redundancy by choosing their corresponding probing range. However, if nodes have different sensing ranges it is hard to find a relationship between the probing range and the desired redundancy.

Tian and Georganas [12] propose an algorithm that provides complete coverage using the concept of sponsored area. The authors present a basic model for a coverage-based off-duty eligibility rule and back-off scheme. But the algorithm results in more active nodes because of the imprecise coverage degree calculation.

Ye et al., in [13] present a probing-based density control algorithm, named PEAS, which depends on location information to derive redundancy and allows redundant nodes to fall asleep. In the PEAS, some nodes work continuously and die prematurely. This causes the uneven distribution of nodes' energy consumption across the network, reducing the quality of the network coverage. Thus, in PEAS, a sensing hole takes place permanently once it occurs. Furthermore, it may cause partitioning of the network or isolation of nodes.

PECAS [26] is a collaborating adaptive sleeping scheme to improve PEAS. Unlike PEAS, PECAS informs the probing node of the next sleep time of a current working sensor node in the reply message. It allows probing nodes to substitute for the current working node right after the working nodes goes to sleep to reduce the permanent sensing holes.

From the abovementioned protocol descriptions, it is apparent that the existing node scheduling protocols treat coverage and connectivity separately. Moreover, the scheduling algorithms should be aiming to achieve longer lifetime for the network. One basic requirement for maximizing the lifetime of WSNs is to assure even distribution of energy consumption [20, 21]. Therefore, the node scheduling algorithm has to be designed to distribute energy consumption properly. In addition, there are a few more requirements for the node scheduling algorithm, which are listed below:

i) Self-configuration of sensor nodes should be mandated because it is inconvenient or impossible to manually configure sensor nodes after they have been deployed in hostile or remote working environments.

ii) The design has to be fully distributed, because a centralized algorithm needs global synchronization overheads, and is not scalable to large populated networks [28].

iii) The scheduling algorithm should allow the maximum number of nodes to be turned off for most of the time. At the same time, it should preserve the required sensing coverage.

iv) The scheduling scheme should be able to maintain the system reliability. As sensor nodes die at any time in WSNs, a certain amount of redundancy is thus needed to provide the reliability.

Following the above mentioned requirement, in this paper we propose a coverage-based node scheduling protocol which provides the required coverage maintaining minimal number of sensor nodes, and at the same time ensuring connectivity of the network. Each node in the network autonomously and periodically decides itself on whether to turn on or turn off itself using only local neighbours' information. To preserve sensing coverage, each node decides to turn itself off when it discovers that it overlaps a certain amount of its sensing area with its neighbours. The sensor nodes selected by the proposed scheduling algorithm can take part constructing different logical topologies. For example, both in [17, 29] multiple chains are constructed using all sensors deployed in the target field. However, we propose that, this node scheduling algorithm can be run before these protocols start creating chains. Thus, a high number of sensor nodes can be turned off, and this will save huge energy for the network.

2 Definitions and Problem Statement

Assume a set of sensor nodes $\aleph = \{S_1, S_2, ...\}$ are randomly deployed on a target field Δ. A scheduling algorithm has to be designed so that it selects a set of sensor nodes, Ω, where $\Omega \subseteq \aleph$. Based on this requirement, this section describes the definitions of necessary terminology for the proposed node scheduling algorithm.

Definition 1: Sensing Region. The sensing region of a sensor node S_i, denoted as $C(S_i)$, is the amount of area that is inside the sensing range of the sensor node S_i. To make the calculations simple, it is assumed that the sensing region of a sensor node is represented by a circle, and all sensor nodes have the same sensing ranges. These assumptions can be made without the loss of generality, and are used in many other research works, such as [18, 19].

Definition 2: Neighbour. A node S_j is a neighbour of node S_i, if and only if sensing regions $C(S_j)$ and $C(S_i)$ intersect. Thus, the neighbour set of the node S_i, denoted as $\psi(S_i)$, can be defined as:

$\psi(S_i) = \{S_j | S_j \in \aleph, d(S_i, S_j) < 2r, i \neq j\}$ where $d(S_i, S_j)$ denotes the Euclidian distance between the nodes S_i and S_j, and where r is the radius of the sensing region of the nodes S_i and S_j.

Definition 3: Rank. The rank of a sensor node S_i, denoted as $\Re(S_i)$, is defined by the cardinality of its neighbour set $\psi(S_i)$. Thus, if the sensor node S_i has a higher number of neighbours than the sensor node S_j, the sensor node S_i's rank has a higher value than that of the sensor node S_j.

Definition 4: Shared sensing region. Shared sensing region of a sensor node S_i, denoted as $\xi(S_i)$, is defined as the fraction of S_i's sensing region, that the sensor node S_i shares with its neighbouring sensor nodes. Thus,

$\xi(S_i) = \bigcup\{S_i \cap S_j | \forall S_j \in \psi(S_i)\}$

Definition 5: Deployment density. Deployment density, δ describes how evenly the sensor nodes are deployed in the target field Δ. Assuming that $|\aleph|\pi r^2 > \Delta$ (i.e., there are sufficient numbers of sensor nodes to cover the target field), deployment density δ is defined as the ratio between the maximum areas that can be covered by all disjoint sensor nodes to the actual areas covered in the target field Δ by the deployed sensor nodes.

Thus, deployment density, $\delta = \frac{|\aleph|\pi r^2}{\bigcup\{C(S_i)|S_i \in \aleph\}}$ (1)

Definition 6: Coverage Ratio. Denoted by λ, the coverage ratio defines the portion of the sensor field which need to be covered by the selected sensor nodes. Coverage ratio can be calculated by the ratio between the total coverage area by the selected sensor nodes to the coverage area by all deployed sensor nodes. Obviously, increasing the coverage ratio makes the coverage quality of the network better.

Definition 7: k-Covered. If a point *p* is covered by at least *k* number of sensor nodes, the point *p* is called *k*-covered. That is, the point *p*'s coverage degree is *k*. Coverage degree is used as the measure of quality of coverage service (*Q*o*CS*). Customarily, the higher the coverage degree, the better the coverage quality of the network.

Problem statement

In most relevant works, the problem about *k*-covered is related to the question of how all points of the target region would be covered by at least *k* number of sensor nodes. However, for a certain kind of applications, *k*-covered is not always essential. For example, some applications do not require every point in the target field to be *k*-covered. This is sufficient to achieve a certain coverage ratio. For example, 80%-90% coverage ratio, or even less is adequate for a WSN to estimate air pressure, temperature, humidity or to detect an event like forest fire. Moreover, when sensor nodes are deployed randomly in a target field, the sensor nodes may not even cover 100% of the target area. Based on this, a novel problem of *QoCS* of 1-covered with λ% coverage ratio is proposed. This paper defines the node scheduling problem as follows: given the deployment density δ, the question is to find a minimal number of nodes such that the coverage ratio is at least λ% of the target network.

3 Description of the Proposed Algorithm

This section describes the proposed node scheduling algorithm in detail. The section consists of several sub-sections which describe different issues, methods and calculations for the proposed node scheduling algorithm.

3.1 Identifying node selection criteria

In the proposed node scheduling algorithm, four specific criteria have been considered. Based on these criteria, the priority of each node is defined. For each sensor node, these criteria are: number of neighbours of the node, the node's shared sensing region with its neighbours, residual energy of the sensor node and repeated selection number of the node (i.e., number of times the node was selected earlier). The justifications for these criteria are described below.

The first criterion that should be chosen for the scheduling algorithm is the number of neighbours of each node. If a node does not have any neighbouring node at all, this node must be selected. Otherwise, the sensor node's sensing region cannot be sensed by any other sensor node(s). On the other hand, if a node is surrounded by many other sensor nodes, that node's coverage area can be sensed by the node's neighbouring nodes. Thus the node with many neighbours can be turned off.

The second criterion should be the shared sensing region $(\xi(x))$ of each sensor node with its neighbouring nodes. For any two sensor nodes S_i and S_j, the relation $\xi(S_i) > \xi(S_j)$ means that the sensor node S_i shares a comparatively larger area with its neighbouring sensor node(s) than the sensor node S_j does. Note that, the value $\xi(x)$ does not depend on the number of neighbours. Thus, if the sensing region of a node overlaps a large amount of area with its neighbours, the node can be replaced by one of its neighbouring nodes. As a result, sensor nodes which share small areas with their neighbouring nodes should have higher priority to be selected.

The third criterion to be considered during node selection is the residual energy of the sensor nodes. A sensor node which has lost a considerable amount of its battery energy should be avoided, unless there is no other way but to select the node. Selecting such a node accelerates the death of the sensor node, and this negatively affects the network lifetime [20, 21].

The fourth and last criterion should be the repetition of selection of a sensor node. If the same sensor node is selected over and over again, the node loses its energy very quickly, and his situation adversely affects the lifetime of the network [20, 21]. Thus, the node scheduling algorithm should be fair for each sensor, so that each sensor is selected at least one time in a specific period of time.

After determining the node selection criteria, the next step for the proposed node scheduling algorithm is to construct specific rules that the algorithm would follow in order to select appropriate sensor nodes. The following sub-section uses the criteria discussed in this section to construct the required set of rules.

3.2 Node scheduling rules

The proposed node scheduling algorithm would follow a set of rules to schedule the sensor nodes. These rules are derived using the selection criteria, and to meet the algorithm requirements. These rules specify which node is to be selected, which should not be selected, and which should be prioritized. The node scheduling rules are as follows:

i) To make the node scheduling algorithm distributed and independent from locations of sensor nodes, each node should autonomously and periodically decide whether to go to sleep mode, or to keep itself active. In making this decision, each node would consider the following issues: residual energy of the node, number of its neighbouring nodes and number of times the node was selected previously.

ii) A sensor node with a higher level of energy holds a higher chance of being selected than a sensor node with a lower energy level. Otherwise, energy consumption throughout the network would not be evenly distributed.

iii) A sensor node with a lower rank should be prioritized to be selected, compared to those with higher ranks, because a high-ranked sensor node has a higher possibility to be redundant than a low-ranked sensor node.

iv) A sensor node which shares a comparatively smaller area of its sensing region with its neighbouring sensor nodes holds higher priority to be selected.

v) Among deployed sensor nodes, a set of sensor nodes are selected by the scheduling algorithm to ensure minimum l% of coverage by the selected sensor nodes. On the other hand, as soon as desired l% of coverage is achieved, the node scheduling algorithm stops selecting any further sensor node.

After establishing the rules for scheduling sensor nodes, the next task is to apply these rules for each sensor node. The methods of applying the node scheduling rules for each sensor network are described in the following sub-section.

3.3 Applying node scheduling rules to select sensor nodes

The main idea for scheduling sensor nodes is to use the redundancy in sensing regions, and to offer the user to select the coverage ratio (λ) necessary for the specific application. Depending on the value of coverage ratio λ and deployed density δ, the proposed node scheduling algorithm is able to determine the minimum number of sensor nodes required to achieve the coverage ratio λ. Different steps involved in the node scheduling algorithm are described below.

In the proposed node scheduling algorithm, each sensor node makes its own decision depending on the information it collects from its neighbouring nodes. This decision is made by each sensor node at the start of the node scheduling algorithm. To make this decision, each sensor node generates a pseudorandom number, using the seed state that includes two pieces of information, which are i) residual energy of the node, and ii) number of times the node was previously selected. The sensor node then informs this pseudorandom number to all of its neighbours using a '*hello*' message. If the generated pseudorandom number is less than a threshold value, the node decides to take part in the scheduling process. The node then informs its willingness to join the scheduling process by sending '*notify*' messages to all of its neighbouring sensor nodes. On the other hand, if the generated pseudorandom number is greater than the threshold value, the sensor node does not do anything.

A sensor node that is not participating in the scheduling process, discards any '*notify*' messages from its neighbouring sensor nodes. On the other hand, sensor nodes participating in the scheduling process collect all '*notify*' messages from their neighbouring sensor nodes. From the collected '*notify*' messages, each participating sensor node calculates two parameters, namely i) its rank and ii) the shared sensing ranges with its neighbours. These two parameters would be used in the scheduling process in the following way.

The rank of a sensor node is defined by the cardinality of its neighbour set (see Section 4.3). For example, if a sensor node does not have any neighbour, its rank is zero; if there is a single neighbour, the rank of the node is one, and so on. According to the node scheduling rules, a sensor node with a lower rank enjoys higher priority to be selected than a sensor node with higher rank, and vice versa. Thus node selection procedure starts with the sensors with lower ranks. The sensors with rank zero are considered first; after that sensors with rank one are considered, and so on.

To consider whether a sensor node S_i is to be selected or not, its shared sensing region ($\xi(S_i)$) with the currently selected neighbouring sensor nodes is calculated. This is because if a sensor node is not selected by the scheduling algorithm, there is no point to counting the sensor node as a neighbour. For clarification, consider the sensor node S_i has four neighbouring sensor nodes, S_m, S_n, S_o and S_p. Among the neighbours, for example, the sensor nodes S_m and S_o have already been selected. While the sensor node S_i would determine whether or not it would be selected, the sensor node S_i calculates $\xi(S_i)$. In calculating $\xi(S_i)$, the sensor node S_i considers only two of its selected neighbouring nodes S_m and S_o. In other words, the sensor node S_i does not consider the sensor nodes S_n and S_p in calculating $\xi(S_i)$. For the sensor node S_i, after calculating $\xi(S_i)$, this value is compared with a threshold value $\xi_{\max}$. In this proposed node scheduling algorithm, this threshold value is called '*maximum allowed shared sensing region*'. The sensor node is selected if $\xi(S_i) \leq \xi_{\max}$, otherwise the sensor node S_i is turned off.

The following two sub-sections describe how a sensor node Si calculates $\xi(S_i)$ and how $\xi_{\max}$ value is estimated. Note that, as it is assumed that the sensors are deployed randomly in the target field, it is not feasible to provide a fixed valued for $\xi_{\max}$.

3.3.1 Shared sensing region calculation

Assume the sensing range of a sensor node S_i is *r*. By definition, a node's sensing region is a circle centred at this node with radius *r*, if all nodes lie on a 2-dimensional plane. To simplify the calculation, consider only two neighbouring nodes S_i and S_j. The shared area by the two sensor nodes S_i and S_j

$\xi(S_i, S_j) = r^2\alpha - dr\sin(\alpha/2) = 2r^2\arccos(\alpha/2) - dr\sin(\arccos(d/2r))$, where α is the angle created in the centre of a sensing region by connecting two intersecting points of the sensing regions.

Using this equation, the sensor node S_i can easily find out the shared sensing area if the sensor node S_i has only a single neighbour. However, in most of the cases, a sensor node has more than one neighbour. Let a sensor node S_i has *m* number of neighbours. $\psi(S_i) = \{S_1, S_2, ..., S_m\}$. Further assume, $\xi(S_i, S_1) = A_1$, $\xi(S_i, S_2) = A_2$, ..., $\xi(S_i, S_m) = A_m$ Without loss of generality, it can be assumed that a higher number of neighbours produce higher probability to coincide the sensor node S_i's shared areas with its neighbouring sensor nodes. Also assume, $d(S_i, S_1) \le d(S_i, S_2) \le \cdots \le d(S_i, S_m)$ (i.e., S_1 is the closest neighbour of S_i whereas S_m is the furthest neighbour of S_i). Thus, $A_1 \ge A_2 \ge \cdots \ge A_m$

To calculate the shared sensing region of S_i with its neighbour nodes, the contributions of each sensor node (from the closest to the furthest) is considered. Essentially, the closest neighbour contributes the most. Thus, considering the first neighbour S_1, $\xi(S_i) = A_1$

Considering the second neighbour S_2, $\xi(S_i) = A_1 + A_2 - (A_1 \cap A_2)$

Considering the third neighbour S_3, $\xi(S_i) = A_1 + A_2 + A_3 - (A_1 \cap A_2 + A_2 \cap A_3 + A_3 \cap A_1 + A_1 \cap A_2 \cap A_3)$ ...and so on.

Now, finding the value of common areas of shared regions (such as $A_1 \cap A_2 \cap A_3$) is not trivial. As the number of neighbours increases, the complexity of the computation also increases exponentially. This computation may not be suitable for resource constrained sensor nodes. For this reason, a heuristic approach is adopted. This approach is described below.

Consider the calculation of $A_1 \cap A_2$. Two extreme cases can be assumed, where in one extreme case, A_1 and A_2 are disjoint. In this case the contribution of the second neighbour to $\xi(S_i)$ is the whole shared area A_2. On other extreme case, the shared area of the second neighbour A_2 is be fully covered by the A_1 . In this case the contribution of the second neighbour to $\xi(S_i)$ is zero. The heuristic followed in this case is to take the average of the two extreme cases. Thus, using this heuristic, $A_1 \cap A_2 = \frac{A_2}{2}$. Therefore, after considering the second neighbour S_2, $\xi(S_i) = A_1 + A_2 - (A_1 \cap A_2) \approx A_1 + \frac{A_2}{2}$

Now, applying the heuristics, $A_1 \cap A_3 + A_2 \cap A_3 - A_1 \cap A_2 \cap A_3 = \frac{A_3}{2} + \frac{A_3}{2} - \frac{A_3}{3}$

Therefore, after considering the third neighbour S_3,

$\xi(S_i) = A_1 + A_2 + A_3 - (A_1 \cap A_2 + A_2 \cap A_3 + A_3 \cap A_1 + A_1 \cap A_2 \cap A_3) \approx A_1 + \frac{A_2}{2} + \frac{A_3}{3}$

Thus, it can be shown that the total shared sensing region of S_i with its neighbours,

$$\xi(S_i) \approx \xi(S_i, S_1) + \frac{1}{2}\xi(S_i, S_2) + \frac{1}{3}\xi(S_i, S_3) + \cdots + \frac{1}{m}\xi(S_i, S_m) = \sum_{j=1}^{m} \frac{\xi(S_i, S_j)}{j} \quad (3)$$

Equation (3) is used to calculate the total shared sensing region of a sensor node S_i in respect to its neighbouring nodes which have already been selected. If the calculated value of $\xi(S_i)$ is less than or equal to $\xi_{\max}$, the sensor node S_i is selected, otherwise it is turned off. How to estimate the value of $\xi_{\max}$ is shown below.

3.3.2 Estimate maximum shared sensing region ($\xi_{\max}$) value

Selecting the value for $\xi_{\max}$ is crucial. If $\xi_{\max}$ value is too small, the scheduling process would require a longer period of time. On the other hand, choosing a very large $\xi_{\max}$ actually diminishes the efficiency of the algorithm. Also note that random deployment of the sensor nodes in the target field precludes a predetermined value of $\xi_{\max}$. The value of $\xi_{\max}$ mainly depends on deployed density (δ) of the sensor nodes. Deployed density (δ) is calculated using the definitions discussed in Section 3. Figure 1 shows the relationship among deployed density (δ), maximum shared sensing region allowed ($\xi_{\max}$) and normalized coverage ratio (λ). For example, if the deployment density is 3.3, and the user requires a coverage ratio λ = 90%, the algorithm starts with the value of maximum shared sensing region $\xi_{\max}$ = 25%. Using this algorithm, however, the value of $\xi_{\max}$ can be estimated as closely as possible. Using these estimations and calculations, sensor nodes are selected. The entire node scheduling algorithm is shown in Figure 2.

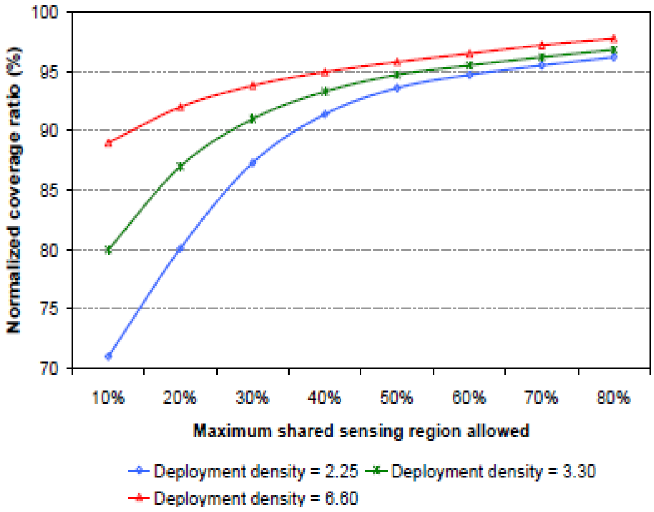


Fig. 1 $\xi_{\max}$ vs λ

3.4 Scheduling states and transitions

This sub-section describes the different states and their transitions during the sensor network runs using our logical topology. It is found in [17] that reconstruction of a chain is required when around 20% of its member nodes die. The node scheduling scheme aims to engage only a subset of the deployed nodes in the field to construct chains. Intuitively, this leaves an option to change the member nodes of a chain more frequently. This helps energy dissipation by the sensor nodes to be more evenly, and thus increases the lifetime of the network. In the proposed node scheduling algorithm, all the nodes stay in one of the three states: i) waiting state ii) sleeping state and iii) working state.

At the very initial stage (just after the sensor deployment), or after the end of each chain construction round, all the nodes are in waiting state. Each node waits for a random back-off time (to avoid collisions), and then broadcasts a '*hello*' message. It is used for a node to collect the pseudorandom numbers generated by its neighbour nodes. Each node maintains a neighbour table and refreshes it periodically. Maintaining the pseudorandom numbers of neighbours is worthwhile when a sensor node in sleeping state has to take part in the scheduling procedure to make up coverage ratio.

In other words, in waiting state, a node broadcasts a '*hello*' message. It then makes decision whether or not to take part in the scheduling procedure, and then notifies its intension sending a '*notify*' message. When a node does not take part in the scheduling procedure, it goes to sleeping mode directly without notifying its neighbours. On the other hand, if a node takes part in the scheduling procedure and is selected, it enters the working state, otherwise it goes to sleeping state. At the end of a new chain construction round, all nodes come back to waiting state. In working state, a node actively monitors the area and takes part in communication along the chain. A node remains in working state until the beginning of a chain construction round. It is assumed that when a node fails, it simply stops working and does not send or receive any messages.

4 Mathematical Analysis

The mathematical model is to validate the simulation results. The results from this mathematical model will be matched with the simulation results and compared.

Let the target field Δ has an area α^2. Further, assume $q \subseteq \Delta$ be the part of the target field Δ, which will be covered by the circular sensing ranges of *k* number of sensor nodes residing in the target field. Then, the ratio of $area(q)$ to α^2, where $area(q)$ denotes the area of q, is the user's desired sensing coverage at each reporting round. Any point $(x, y) \in \Delta$ is considered to be covered if it is inside the circular sensing coverage of a selected sensor node in the target field. To measure the probabilistic sensing coverage, the probability of a point $(x, y) \in \Delta$ not to be covered by a selected sensor node S_i, $P(1)_q^i(x, y)$ is measured. Let (u, v) be the location of Sensor S_i, and $A(x, y)$ be a circular area centred at point (*x*, *y*) with radius *r*. Then, the point will not be covered when $(u, v) \in \Delta - A(x, y)$. Therefore, the probability of the point (x, y) not to be covered by a randomly selected sensor node, is given by:

```
Deployed set of sensor nodes, ℵ = {S_1, S_2, ⋯}
Selected set of sensor nodes Ω = φ
Expected coverage ratio λ
Deployed density δ
Threshold T = f (δ, λ, Λ )

Initial phase
for each sensor node S_i ∈ ℵ
    generate pseudorandom number PR_{S_i} = f(x, E_r)
        // x is the number of times the node was selected earlier
        // E_r is the node's residual energy
send hello message to all neighbours
if (PR_{S_i} ≤ T) send notify message to all neighbours

Starting phase
for each sensor node S_i ∈ ℵ
    if S_i does not participate in scheduling process
        while(1)
            wait for wakeup message
    if S_i participates in scheduling process
        construct neighbour set ψ(S_i)
Arrange all members of ψ(S_i) using ascending values of the distance from S_i
Assign Rank Ŕ(S_i)
Assign estimated maximum allowed shared sensing region ξ_max = f (δ, λ)

Scheduling phase
while coverage ratio achieved < λ
    for each sensor node S_i ∈ ℵ from lower to higher ranks
        Calculate ξ(S_i) with respect to all S_j such that S_j ∈ ψ(S_i) & S_j ∈ Ω
        if (ξ(S_i) ≤ ξ_max)
            Ω = Ω ∪ S_i
        Adjust coverage ratio achieved
    Calibrate ξ_max
```

Fig. 2 Coverage-based node scheduling algorithm

$$P(1)_q^i(x,y) = \int_{(u,v)\in\Delta - A(x,y)}\int \phi(u,v)\,du\,dv \tag{4}$$

where $\phi(u,v) = \frac{1}{\alpha^2}$ is the probability of S_i to be located on a point $(x,y)\in\Delta$. Equation (4) represents the fraction of Δ not covered by a randomly-selected sensor node's circular sensing range. Thus, the probability of a point not covered by randomly selected k sensor nodes is obtained as:

$$P(k)_q(x,y) = \prod_{i=1}^{k}(P(1)_q^i(x,y))^i \tag{5}$$

Let $\overline{q}$ be the area that is not covered. For randomly selected k sensor nodes, the expected value of q can be given by:

$$E[\overline{q}] = \int_{\Delta}\int P(k)_q(x,y)\,dx\,dy \tag{6}$$

Now, consider how much area in Δ can be covered by randomly-selected k sensor nodes. For this purpose, consider the fraction of Δ not covered by these k sensor nodes within Δ. This can be obtained by dividing $E[\overline{q}]$ (Equation 6) by the area of Δ, α^2 assuming all (x,y) points are uniformly distributed over Δ. Using Equations (4) and (6), the fraction of Δ not covered by k selected sensor nodes, is given as:

$$E\left[\frac{\overline{q}}{\alpha^2}\right] = \left(\frac{\Delta - A(x,y)}{\Delta}\right)^k = \left(\frac{\alpha^2 - \pi r^2}{\alpha^2}\right)^k \tag{7}$$

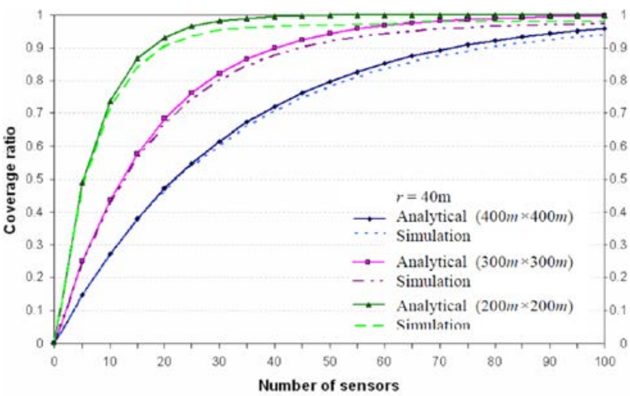
Finally, when k sensor nodes are randomly selected, the probabilistic sensing coverage that any point of Δ will be covered by at least one of k selected sensor nodes' circular sensing range is equivalent to the desired coverage ratio λ. Thus,

$$\lambda = 1 - E\left[\frac{\bar{q}}{\alpha^2}\right] = 1 - \left(\frac{\alpha^2 - \pi r^2}{\alpha^2}\right)^k \qquad (8)$$

Therefore, the smallest integer k which meets the desired sensing coverage, λ, can be defined as:

$$k = \left\lceil \frac{\log(1-\lambda)}{\log\left(\frac{\alpha^2 - \pi r^2}{\alpha^2}\right)} \right\rceil \qquad (9)$$

In order to verify the correctness of k, the analytical model is simulated, and the simulation results are compared with the numerical results measured from Equation (8). Figures 3(a) and (b) show the comparison of the results in covering a requested portion of the monitored area with varying network sizes and sensor nodes' circular sensing ranges. The simulation results shown in each plot correspond to the average of 100 simulation runs. Regardless of the sizes of the network and sensing range, it can be observed in Figures 3(a) and (b) that both the numerical and simulation results are found to match well.



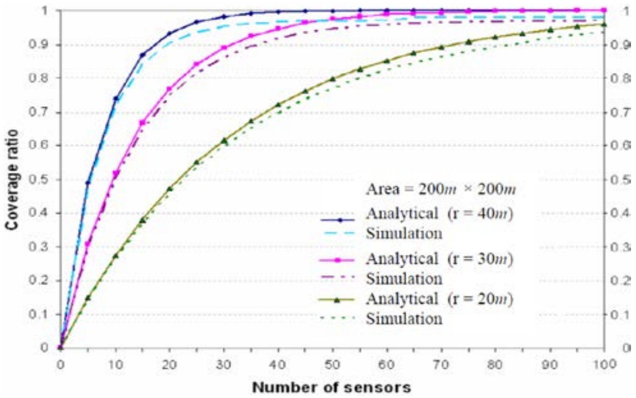


Fig. 3 Comparison of simulation and analytical results for covering a target filed.

5 Experimental Results

This section evaluates the performance of the proposed node scheduling algorithm based on various experimental results. The proposed node scheduling algorithm is compared with a method which selects a same number of sensor nodes using uniform distribution. Figure 4 shows the comparison of the scheduling algorithm with randomly chosen nodes from uniformly distributed nodes. For example, to achieve the coverage ratio λ= 80% while uniform distribution method needs around 50 nodes, the proposed algorithm needs to select only 35 nodes to produce the same coverage ratio. Because in the proposed algorithm, nodes are selected on the basis of shared sensing regions, the selected nodes effectively produce better coverage ratio.

Figure 5 shows the comparative energy consumption of the proposed method with that of COSEN and PEGASIS. PEGASIS is chosen in this case, because PEGASIS is also a chain oriented algorithm which acts like COSEN, except that it uses a single chain. To compare energy consumption, a large value of λ = 92% is chosen. In the experiments it was found that, by offering 92% coverage ratio, the proposed scheduling algorithm saves around 21% energy than COSEN in 500 rounds. Figure 6 shows the network lifetime patterns using PEGASIS, COSEN and the proposed algorithm. In PEGASIS, the first node dies at around 350 rounds, and 90% sensor nodes die at around 600 rounds. In contrast, using COSEN, the first nodes dies at about 400 and more than 90% sensor nodes die at around 550 rounds. Using the proposed algorithm however, it was found that the first node dies at around 500 rounds and 90% of the sensor nodes die after 875 rounds. That means for $\lambda \approx$ 90%, the proposed algorithm doubles the lifetime of network. If the user requires less coverage ratio, the lifetime can be extended even further.

In addition, to verify the effectiveness of the proposed node scheduling algorithm, extensive simulation experiments were performed to compare the performance of the proposed algorithm with PEAS and PECAS. The reason why these two protocols were chosen is that these two protocols also schedule nodes based on coverage of the target field. The comparison was performed in terms of number of live nodes over time period. A live node is a node which has remaining energy and is in one of three states (working, sleeping and waiting). In PEAS, more sensors are in working state but a large part of their sensing area is redundantly overlapped by their neighbours' sensing area. Thus the sensing coverage is not sufficient over time due to the fact that sensors die rapidly. In PECAS, which is an advanced version of the PEAS in terms of energy balance, more sensors also maintain a working state in its early stages.

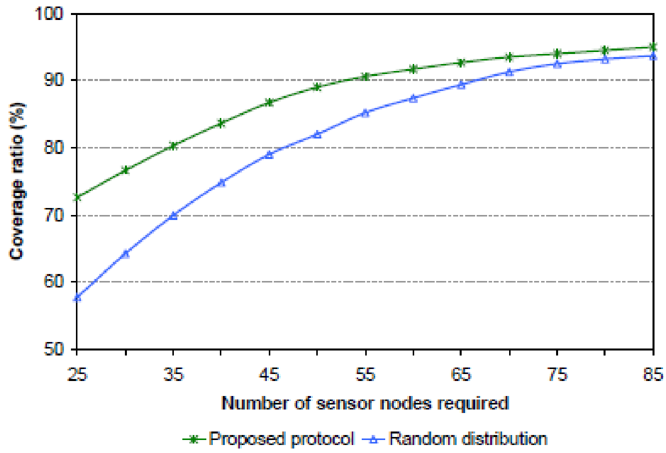


Fig. 4 Comparison of proposed node scheduling algorithm with a method which chooses nodes randomly. ($|\aleph|=100$; $\Delta=400m\times400m$; $r=40$m).

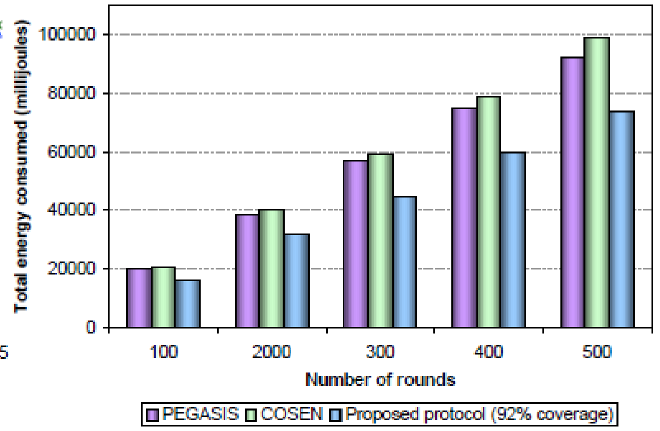


Fig. 5 Energy dissipation comparison among PEGASIS, COSEN and proposed protocol. ($|\aleph|=100$; $\Delta=50m\times50m$; $r=10m$; $\lambda= 92\%$; $\delta = 2.7$).

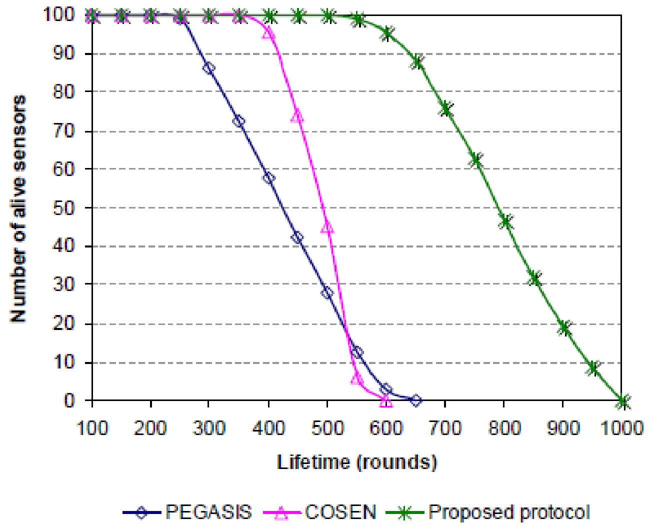


Fig. 6 Lifetime pattern comparison among PEGASIS, COSEN and proposed protocol. ($|\aleph|=100$; $\Delta=50m\times50m$; $r=10m$; $\lambda= 92\%$; $\delta = 2.7$).

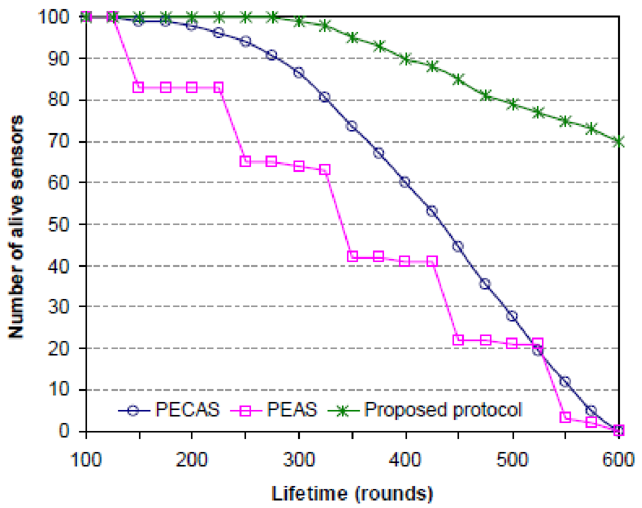


Fig. 7 Comparison among proposed node scheduling algorithm, PEAS and PECAS. ($|\aleph|=200$; $\Delta=200m\times200m$; $r=30m$; $\lambda= 95\%$; $\delta = 1.92$).

PECAS has a slightly longer lifetime than PEAS. Nevertheless, its sensing coverage is similar to that of PEAS with time. It was observed that the proposed node scheduling algorithm performed much better than PEAS and PECAS in terms of number of live nodes over time. Figure 7 shows the comparison among these three protocols using λ = 95% for 200 sensor deployed in a $200m\times200m$ target field with a deployment density of δ = 1.92.

6 Conclusion

This paper proposes a coverage-based node scheduling algorithm. The node scheduling scheme is motivated by the reason that some applications of wireless sensor networks do not require 100% coverage. Furthermore, in a target field, sensor nodes are usually deployed densely, and this creates redundancy. By exploiting both redundancy of sensor nodes and the requirement of less than 100% of coverage, the proposed member node selection/scheduling algorithm is developed. As the algorithm selects nodes based on neighbouring information, the node scheduling algorithm also ensures connectivity. The primary criteria used to schedule sensor nodes are: number of neighbours, amount of shared sensing of the sensors, residual energy and repetition of selection number. Simulation results show that the proposed node scheduling algorithm saves a significant amount of energy, while sacrificing only a little amount of coverage. For example, the proposed scheduling algorithm saves more than 20% energy as compared to the conventional chain-oriented algorithm while reducing only 7% - 8% of the coverage ratio. For various applications, such as temperature/humidity or sea level monitoring or forest fire detection systems, where 100% coverage is not required, this offers a very useful trade-off to the users. The choice is kept open for the user to calibrate the desired coverage ratio, so that the algorithm selects minimal number of sensor nodes to provide the coverage, at the same time warranting the connectivity of the network.

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